May 18, 2000

Ms. Magalie Salas
Office of the Secretary
Federal Communications Commission
The Portals
445 Twelfth Street, S.W., Room TW-A325
Washington, D.C. 20554

Re: ET Docket 99-231, Amendment of Part 15 of the Commission's Rules Regarding Spread Spectrum Devices

Dear Ms. Salas:

Attached is a copy of a study completed by Lucent Technologies Inc. examining the impact of wideband frequency hopping systems (WBFH) on IEEE 802.11 frequency hopping, 802.11b direct sequence, and Bluetooth systems. Unlike previous submissions, this study focuses on interference levels in a large, multi-floor office/apartment building. Our study demonstrates that the relative interference effect of a WBFH system, on average, is about 28 dB in a typical multi-floor office building. Because they utilize lower power levels, Bluetooth systems experience higher interference levels than IEEE 802.11 systems. These results are consistent with previous studies submitted by IEEE LMSC.

Lucent continues to urge the Commission to consider the negative impact WBFH systems will have on existing products in the unlicensed bands when evaluating the proposals in this proceeding. Lucent supports the compromise proposal submitted by Wireless Ethernet Compatibility Alliance (WECA) which suggests adoption of: 1) a 60 mW power limit for wideband frequency hopping (WBFH) devices; 2) a cap of 100 hops/sec for WBFH devices having channel widths in excess of 1 MHz; 3) receiver performance tests for WBFH systems; 4) a ban on overlapping channels; and 5) a 4 MHz maximum frequency hopping bandwidth. Although the compromise will limit the amount of interference experienced by existing systems, WBFH devices operating under the compromise proposal will still create more interference than a 1 watt 1 MHz system complying with the existing rules. Nevertheless, Lucent believes that the WECA compromise provides reasonable protection for existing systems, while allowing HomeRF manufacturers to obtain higher data rates than currently possible.

Please do not hesitate to contact me should there be any questions.

Sincerely,

Diane Law Hsu

Comparison of Interference with 1 MHz and 4 MHz Frequency Hopping Systems

May 18, 2000

Abstract - **The interference from WBFH (4 MHz wide band frequency hopping) on IEEE 802.11 frequency hopping, 802.11b direct sequence and Bluetooth victim systems is analyzed. A scenario with various assumptions related to path loss inside a multi-floor office building and inside typical residential buildings is considered. The modeling is based on the probability of channel overlap between the 802.11 and Bluetooth victim systems and the WBFH system, and on the number of active WBFH devices within the interference range causing a C/I below the threshold for the victim system in question. The increase in interference for WBFH systems over systems with the current bandwidth limit of 1 MHz is characterized in terms of the power level reduction for the WBFH interferer necessary to equalize the destructive interference for the victim system. This work extends previous work on the subject to include three-dimensional cases and the effect of wall and floor barriers.**

The interference increase caused by the higher frequency hopping bandwidth depends on the emission spectrum shape and on the receiver filtering of the victim. These effects are worked out for a typical receiver filter in combination with the emission spectrum proposed by the supporters of the WBFH Notice.

A summary of the results of two previous papers is given. These previous models are also extended to more directly address some further questions related to the current WBFH Notice.

1.0 Summary

The effect of a frequency hopping bandwidth increase on interference to legacy Part 15 systems is analyzed. The current bandwidth limit is 1 MHz and an increase to 4 MHz is considered. The power level of the 4 MHz system that would cause the same interference probability as a comparable system with 1 MHz bandwidth and a 1 W power level is given. The interfering systems compared operate with the same hopping rate so that the effect of a potential faster hopping rate is neutralized. The interfering Wide Band Frequency Hopping (WBFH) systems have a 4 MHz bandwidth and the Narrow Band Frequency Hopping (NBFH) systems have a 1 MHz bandwidth

The increase in interference for WBFH systems over NBFH systems is most severe for victim systems of narrower bandwidth. Thus, the effect on 1 MHz bandwidth frequency hopping systems is more severe than on direct sequence systems.

The larger bandwidth of the WBFH transmitters makes the risk of frequency overlap with an NBFH receiver a number of times larger than it is with an NBFH transmitter. Apartments and office buildings are analyzed that are examples of practical environments with rectangular shapes and with walls and floors that have a major effect on path loss. The interference power level is characterized as the probability of the received level from 1 W sources that are evenly distributed throughout the building. The cumulative distribution of the probability is developed from a distribution of the positions of transmitters creating the levels. A power level decrease in the WBFH transmitters reduces the building volume in which transmitters are located that create interference at the threshold level of the receivers (and thereby reduces the number of transmitters capable of creating interference accordingly). An offset of several tens of dB is normally required for WBFH transmitters to account for the increase in overlap probability in comparison to that of NBFH transmitters when the interference threshold level is in the order of –70 to –90 dBm. The filtering effect in the NBFH receiver reduces the power level of a WBFH signal a few dB relative to that of an NBFH signal. However, the required reduction in transmit power for WBFH to neutralize the increased incidence of interference is still in the order of magnitude of a few tens of dB.

The relative power level to create equal interference is shown to be greater than 30 dB for some of the frequency hopping victim systems and is usually below about 5 dB for the direct sequence victim systems.

Four typical building configurations were analyzed. These include a large office building and three apartment buildings. The necessary WBFH power level reduction relative to the NBFH power level was shown to be:

WLAN in office building	26 to 28 dB
Victim system of optimum power level in apartment buildings (Bluetooth and IEEE 802.11 type systems)	16 to 18 dB

The office building consists of 5 floors with relatively open office space on each floor. This is a typical environment for application of Wireless LANs (WLANs). The relative WBFH power level compared to the NBFH power level necessary to equalize interference is shown to be about -28 dB when the interfering systems occupy all floors. The IEEE LMSC paper [2] predicts about a 31 dB power reduction in the nearest comparable configuration. This is very close agreement.

The necessary power level difference is about 10 dB less if the interfering system transmitters are excluded from the floor where the victim system is installed.

The effect will be less in a larger building and slightly higher in a smaller building. The IEEE LMSC model predicts that the relative power level difference for equal interference is about 7 dB lower for an office building with twice the linear dimensions (four times area). However, the interference from both the WBFH and NBFH system will be higher in larger buildings with the same interferer density and attenuation conditions. This is the reason a very large building was selected for analysis.

The apartment buildings analyzed are also large in the sense that the interference range of the victim receivers is less than the building dimensions. The effect of the walls, which act as attenuation barriers create this situation in buildings with relatively smaller actual dimensions.

IEEE 802.11 and Bluetooth modulation was assumed in the victim receivers and the relative interference was analyzed for a range of expected receiver levels. The receiver level appropriate for IEEE 802.11 frequency hopping systems in each of the buildings analyzed is about 20 dB higher than that for Bluetooth systems because the typical IEEE 802.11 power level is 100 mW; 20 dB higher than the Bluetooth level of 1 mW. A level about midway between these levels is appropriate for an NBFH system specifically designed for the application. This is the middle receiver level analyzed.

The relative power level difference (NBFH power level - WBFH power level) for each receiver level for the range of apartment buildings was:

Bluetooth level (-70 dBm)	22 to 24 dB
Mid level (-60 dBm)	16 to 18 dB
IEEE 802.11 at 100 mW (-50 dBm)	12 to 13 dB.

The necessary power level difference was about 2 dB less when the interfering system was excluded from the victim premises (apartment unit or floor). An astute apartment dweller can lower the level of interference by careful selection of products, but the relative effect on his legacy system is much higher if his neighbors choose a WBFH system unless the WBFH power level is limited in accord with the above differences.

The most appropriate model for approximating the effect in these apartment buildings is the TIA model [1] with a high attenuation exponent. The effective value of the attenuation exponent due to the presence of the walls was shown to be about 8 at the middle receiver level (-60 dBm) analyzed.

2.0 The Previous Papers on Wideband Frequency Hopping Interference

The interference effect of increasing the bandwidth of Part 15 frequency hopping systems has been studied and reported in two previous papers. TIA Wireless filed a paper in a previous OET docket[1] that showed the effect of frequency hopping interference in a configuration in which the interferers are evenly distributed over a wide area. The IEEE LMSC filed a document describing the effect of increased frequency hopping bandwidth in a two-dimensional configuration in which the interferers and victim exist in a finite isolated area[2]. Lucent Technologies subsequently filed a supplement to the IEEE LMSC paper giving some further results[3]. The TIA model is appropriate for victim receivers located, for example, in an outdoor urban or suburban region in which Part 15 interfering frequency hopping systems exist. It is also appropriate in other cases in which the region of interferer deployment exceeds the interference range of the victim. The LMSC model is appropriate for a Wireless LAN (WLAN) located inside a building in which the region of deployment is of finite size and for all cases in which the interferer deployment radius is less then the interference range of the victim. Both of these papers determined the appropriate interfering power level to equalize interference as a function of the frequency hopping channel bandwidth.

Appendix A is a summary of these previous studies with some enhancement to more adequately cover the questions raised in the WBFH docket.

Appendix A summarizes the TIA paper and uses the TIA model to show the following for systems in which the model is appropriate, that is, for cases where the interferer deployment radius is large compared to the interference range of the victim.

1. If the number of required channels is reduced to n from the current 75, the power level should be reduced by the factor $(n/75)^2$. That is, the power level should be proportional to n^2.
2. If the bandwidth is permitted to be increased to W_{FH} MHz from the current 1 MHz and the full 75 MHz of spectrum is always required to be used, the power level should be reduced by the factor $(1/W_{FH})$. That is, if the full spectrum is used, the power level should be inversely proportional to the hopping channel width.

The propagation loss exponent is assumed to be equal to 4 in these cases. This is appropriate for outdoor urban and suburban environments.

The LMSC paper considers the interfering transmitters to be evenly distributed over a smaller region in which the interference range of the victim receivers exceeds the boundaries of the region containing the interferers. This model is typical of indoor WLAN systems. The relative interfering effect of an increase in frequency hopping bandwidth is worse for victim systems using low power levels in this model.

Appendix A shows the necessary power level decrease for a 4 MHz bandwidth WBFH system using slow frequency hopping for power levels typical of current legacy frequency hopping systems. The effect is worse for fast hopping interferer systems.

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1 Attachment to TIA Wireless Consumer Communications Section (TIA Wireless) Comments in Docket 96-8 “The Effect of System Parameters on the Interference Potential of Frequency Hopping Systems in the ISM Bands”, June 1996.

2 Annex 1 of the IEEE 802 LAN/MAN Standards Committee, Second Ex-parte Letter, filed in ET Docket 99-231. “Interference Potential of WideBand Frequency Hopping Systems on Packet Data Systems” IEEE p802.11 99/205, dated October 2, 1999 and filed October 4, 1999.

3 “Supplement to the Paper on Interference Potential of Wideband Frequency Hopping” Lucent filing in Docket 99-261, February, 2000.

In summary, for typical indoor WLAN systems:

Victim Power Level	Necessary power level reduction for a 4 MHz bandwidth frequency hopper compared to a 1 MHz bandwidth frequency hopper of 1 W power level.
1 W (maximum permissible)	**22 dB** at equal communication cell and interferer areas
100 mW (typical for IEEE LMSC WLANs)	**31 dB** at equal communication cell and interferer areas
1 mW (Bluetooth specification)	**29 dB** at Bluetooth range of 1/5 that of the interfering system radius

The Bluetooth effect tends to be lower because of the lower range of the Bluetooth system relative to the interferer region. The necessary power reduction is less as the area of interferer deployment is increased relative to the cell area. On the other hand, the effect on Bluetooth tends to be higher because of the lower power level. Thus, the effect on a 1 mW Bluetooth system is about the same as that on a 100 mW IEEE 802.11 frequency hopping system.

The necessary power level approaches the value predicted by the TIA paper for very large interference deployment areas. Table A4-2 of appendix A shows the computed level to be –2.5 dB and the level predicted by the TIA model to be –4.5 dB. This is within the range of the computational accuracy.

The LMSC configuration was two-dimensional and was limited to a circular interferer deployment area. It also did not investigate the effect of walls and other attenuation barriers. This paper compliments the previous work and further investigates the interference in three-dimensional configurations including configurations typical of homes and apartments.

3.0 Interference Bandwidth

The probability that a frequency hop transmission interferes with a victim transmission is proportional to the frequency range over which the interference occurs. This frequency range was referred to as the interference bandwidth in the LMSC paper cited previously. The interference bandwidth for 1 and 4 MHz bandwidth GFSK emissions on a victim receiver using a filter scaled from a Surface Acoustic Wave (SAW) filter were computed. The SAW filter is the dominant type of receiver filter used today.

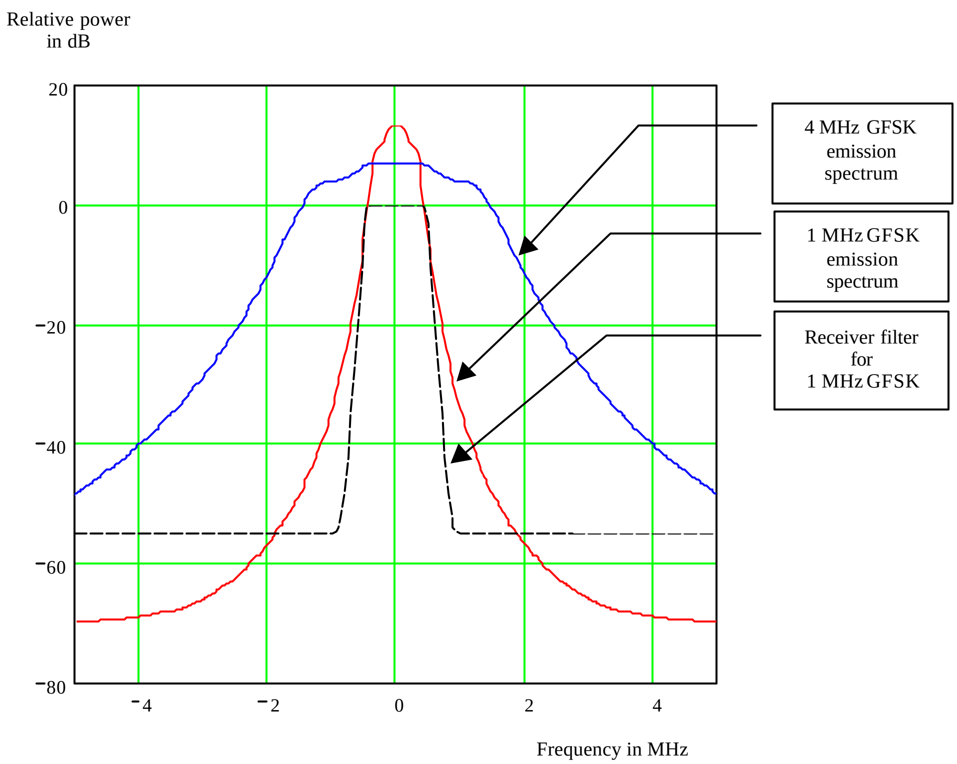


Figure 3-1. Emission spectrum and receiver filter shape with 1 MHz and 4 MHz GFSK frequency hopping systems.

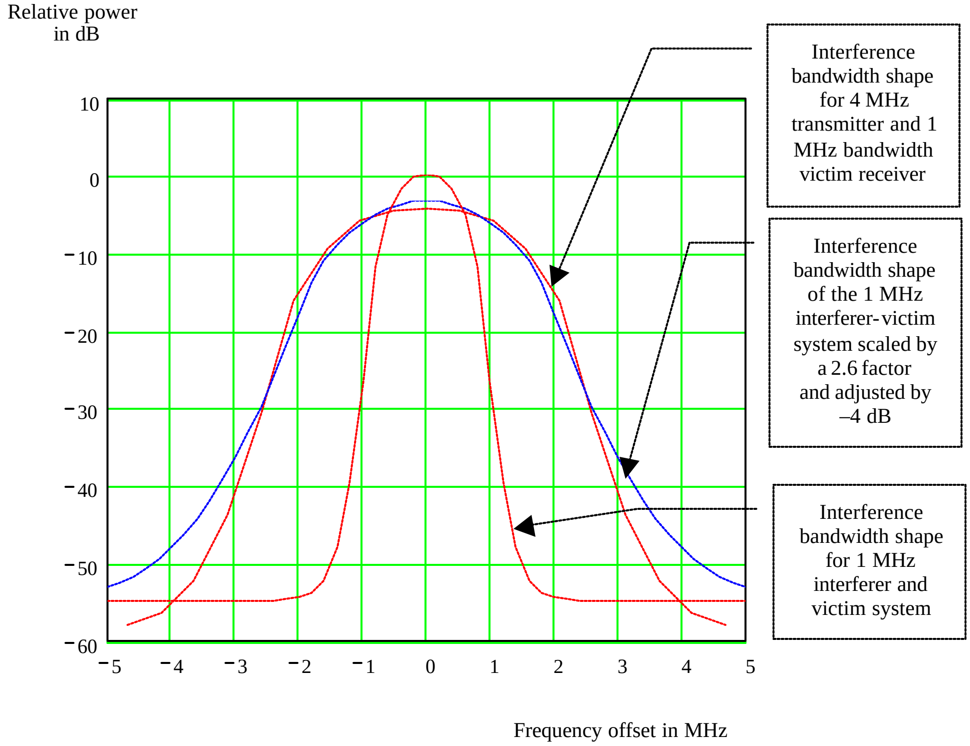


Figure 3 2. Interference bandwidth and power reduction effect with 1 MHz and 4 MHz GFSK frequency hopping systems transmitters and a 1 MHz bandwidth GFSK receiver.

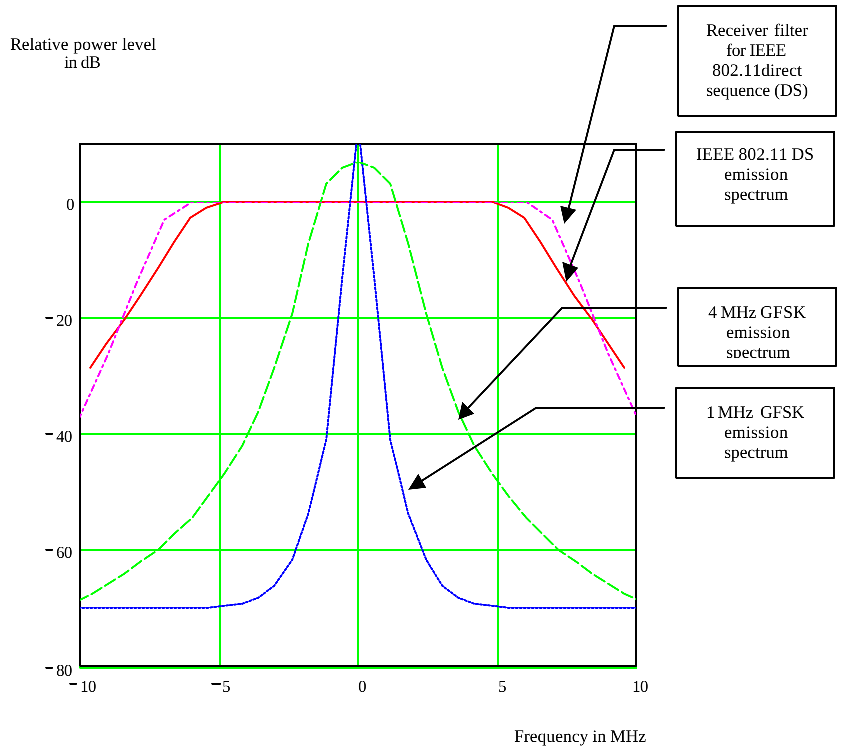


Figure 3-3. Emission spectrum for 1 MHz and 4 MHz GFSK frequency hopping systems and filter shape for IEEE 802.11 direct sequence victim receiver.

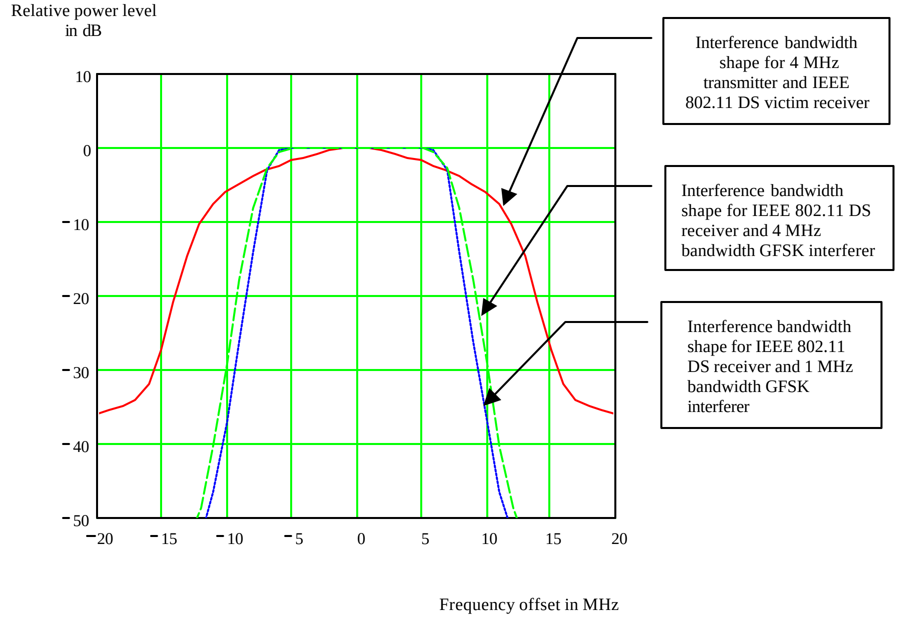


Figure 3-4. Interference bandwidth and power reduction effect with 1 MHz and 4 MHz GFSK frequency hopping systems and an IEEE 802.11 direct sequence victim receiver.

A SAW filter appropriate for a 1 MHz bandwidth GFSK victim system, corresponding to that for systems complying with IEEE 802.11 and Bluetooth frequency hopping systems was considered. Also, a SAW filter of approximately 17 MHz 20 dB bandwidth used in an IEEE 802.11 direct sequence system was used.

Figure 3-1 illustrates the emission spectrum shape for 1 MHz and 4 MHz bandwidth frequency hopping transmitters. The 1 MHz emission bandwidth shape is that of an IEEE 802.11 frequency hopping system and the 4 MHz shape is a linear expansion of the 1 MHz bandwidth shape. The receiver filter of the 1 MHz system is also shown.

Figure 3-2 shows the interference band shape for a receiver filter in a 1 MHz victim frequency hopping system when it is interfered by a 1 MHz or a 4 MHz system transmitter. The interference bandwidth shape of the 1 MHz transmitter-receiver combination is also shown scaled up in frequency by a factor of 2.6 and down in level by 4 dB. The interference frequency profile for the scaled system closely matches that of the 4 MHz transmitter-1 MHz victim bandwidth case. Thus, the interference bandwidth of the 4 MHz bandwidth system on a 1 MHz bandwidth system is 2.6 times as wide as that when both systems bandwidths are 1 MHz. Also, for equal transmitter power, the 1 MHz bandwidth receiver receives 4 dB less power from a 4 MHz transmitter than from a 1 MHz bandwidth transmitter. Thus, for interferer transmitters within interference range and with equal activity, the 4 MHz bandwidth system is 2.6 times more likely to interfere than is a 1 MHz bandwidth system. However, the 4 MHz bandwidth system interference range is less because the effective power level is 4 dB lower. The factor of 2.6 was termed the bandwidth factor and the 4 dB offset was termed β in the IEEE LMSC paper. This terminology will be adopted and:

Bandwidth factor = 2.6
β = 4 dB

for a 4 MHz bandwidth WBFH system and a 1 MHz bandwidth victim system.

Figures 3-3 and 3-4 illustrate the spectrum shaping and power reduction effects for 802.11b victim systems in a similar manner as with Figures 3-1 and 3-2 for 1 MHz frequency hopping victims. The bandwidth factor is about 1.19 in this figure and the wide bandwidth victim receiver receives all of the interference power from a 4 MHz transmitter. Thus,

Bandwidth factor = 1.19
β = 0 dB

for a 4 MHz bandwidth WBFH system and an IEEE 802.11 direct sequence victim system.

4.0 Analysis Technique

We consider multi-floor office and apartment buildings. The apartment buildings consist of multiple units per floor with discrete attenuation in each wall separating the units. Office buildings consist of multiple floors with relatively open spaces on each floor. The walls and floors represent discrete attenuation barriers. Wall attenuation adds linearly with the number of walls on a given floor. However, floor attenuation does not add linearly and the attenuation through N floors is less than N times the attenuation through one floor.

A path loss distance exponent α, as in the previous papers, plus the wall and floor attenuation defines the propagation conditions. Distance dependent attenuation is considered free space at up to 10 meters distance ($\alpha = 2$ for distances up to 10 meters) and the exponent α is considered to be 3.5 for distances above 10 meters. This is consistent with the indoor propagation assumption of the LMSC paper. The mean distance attenuation of the interference signal is computed using this model and the actual interference signal is assumed to have a 5.7 dB standard deviation about this average at a fixed distance. The dB deviation about the average is assumed to follow a normal probability distribution.

The victim system is usually located in the middle most part of the building. Total attenuation between two points consists of the floor attenuation plus the sum of the wall attenuation and the distance attenuation from the interferer to the point directly below or above the victim. One configuration consists of separate buildings. In this case, the inside wall and floor attenuation is the same as above. The outside wall attenuation and building separation attenuation is discussed in the section giving the results.

Illustrations show the building layout and give the loci of the lines of equal average interference power.

The relative interference effect is computed for various victim receive levels for a 4 MHz bandwidth WBFH system compared to a legacy 1 MHz bandwidth system. The interfering systems are considered to consist of transmitters evenly distributed throughout the building. The 1 MHz bandwidth system power level is 1 W and the necessary power level of the 4 MHz system is computed that results in equal interference with the 1 MHz interfering system.

We believe that this attenuation model is sufficiently accurate to show the general effects of attenuation barriers and multiple floors. Further, the previous work provides a means of cross checking the conclusions in the limiting cases.

The victim systems considered are IEEE 802.11 direct sequence and frequency hopping systems and Bluetooth frequency hopping systems. The emission spectrum and receiver and interference passband shapes of these systems are given in section 3. The required C/I ratios are 20 dB for IEEE 802.11 frequency hopping and Bluetooth victim systems and 10 dB for the IEEE 802.11b direct sequence system at 11 Mb/s and 2 dB for the IEEE 802.11b direct sequence system at 2 Mb/s.

The power level decrease necessary to equalize interference is computed by first determining the proportion of 1 MHz interfering transmitters that produce levels above the C/I requirement of the victim then dividing this proportion by the interference bandwidth factor of section 3. This is the proportion of 4 MHz bandwidth systems that will create the same probability of interference. The power level of the 4 MHz system is then determined that would produce the same interference probability if physically distributed over the same area as the 1 MHz interfering system. The receiver filter power reduction (β of the LMSC paper) is taken into account in determining the equalizing power level.

The results are presented as a necessary interference power reduction because this is the proposed method of equalizing interference for WBFH systems. In most cases this can be converted to the necessary distance reduction for legacy systems using the inverse of the propagation model equation. That is, victim systems can compensate for the higher interference potential by reducing their system performance in this manner.

5.0 Large Office Building

This is a large multiple floor office building (80x12 meter, 5 floors). Table 5-1a was prepared from the probability distribution graph of figure 5-2a. The building dimensions are illustrated in figure 5-1 along with an illustration of the constant average receive levels contours at 1 watt transmitter power. Figure 5-2a gives the receiver level probability distribution.

The floor attenuation is 20 dB for single floor separation and 30 dB for two floors.

Table 5-1b was computed from the probability distribution of received levels of figure 5-2b. The steps of the computation are outlined in the table.

Table 5-1a. Power reduction with 4 MHz bandwidth WBFH for multiple floor office building with interference system on all floors.

Victim system	Target receive level of victim system	Tolerable interference level from 1 MHz FH	Area of interference	Area of interference divided by the bandwidth factor	Interference level that corresponds to previous column area	Required reduction in interference level	Reduction corrected by the filtering effect (β)
Bluetooth or 802.11 FH	-60 dBm -70 dBm	-80 dBm -90 dBm	98% 60%	37.6% 38.1%	-57 dBm -58 dBm	23 dB 32 dB	19 dB 28 dB
802.11b at 11 Mb/s	-60 dBm -80 dBm	-70 dBm -90 dBm	69% 99%	58.1% 83.3%	-66 dBm -75 dBm	4 dB 15 dB	4 dB 15 dB

Table 5-1b. Power reduction with 4 MHz bandwidth WBFH for multiple floor office building with no interference system on victim system floor.

Victim system	Target receive level of victim system	Tolerable interference level from 1 MHz FH	Area of interference	Area of interference divided by the bandwidth factor	Interference level that corresponds to previous column area	Required reduction in interference level	Reduction corrected by the filtering effect (β)
Bluetooth or 802.11 FH	-60 dBm -70 dBm	-80 dBm -90 dBm	90% 99%	34.6% 38.1%	-63 dBm -64 dBm	17 dB 26 dB	13 dB 22 dB
802.11b at 11 Mb/s	-60 dBm -80 dBm	-70 dBm -90 dBm	62% 99%	52.2% 83.4%	-67 dBm -76 dBm	3 dB 14 dB	3 dB 14 dB

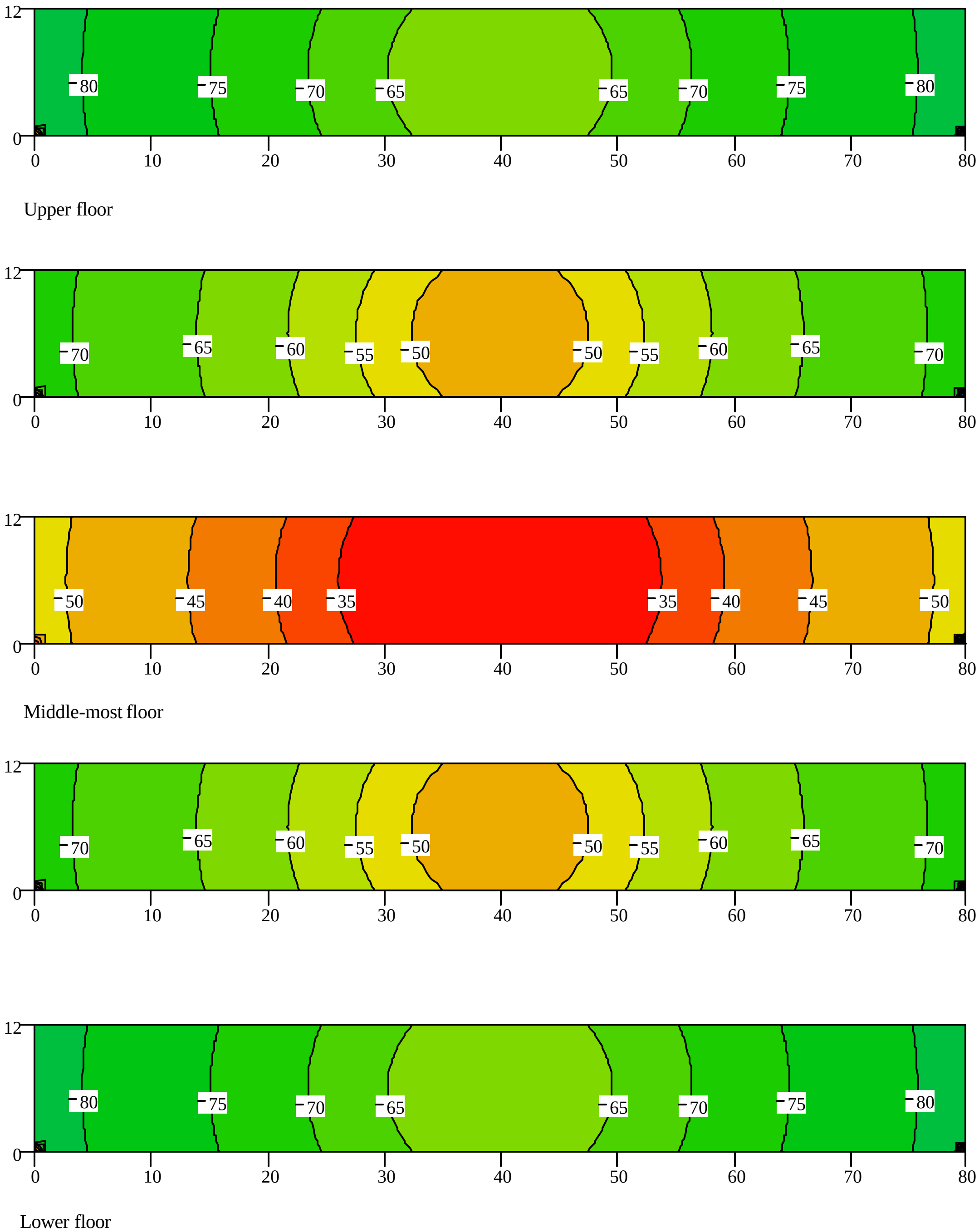


Figure 5-1. Receiver levels around a 30 dBm transmitter at the middle most floor of a large office building. Levels are in dBm. Each floor is 80 meters long and 12 meters wide. By reciprocity, the level produced at the middle point of the building would be the same if the transmitter were located on the corresponding equal level locus.

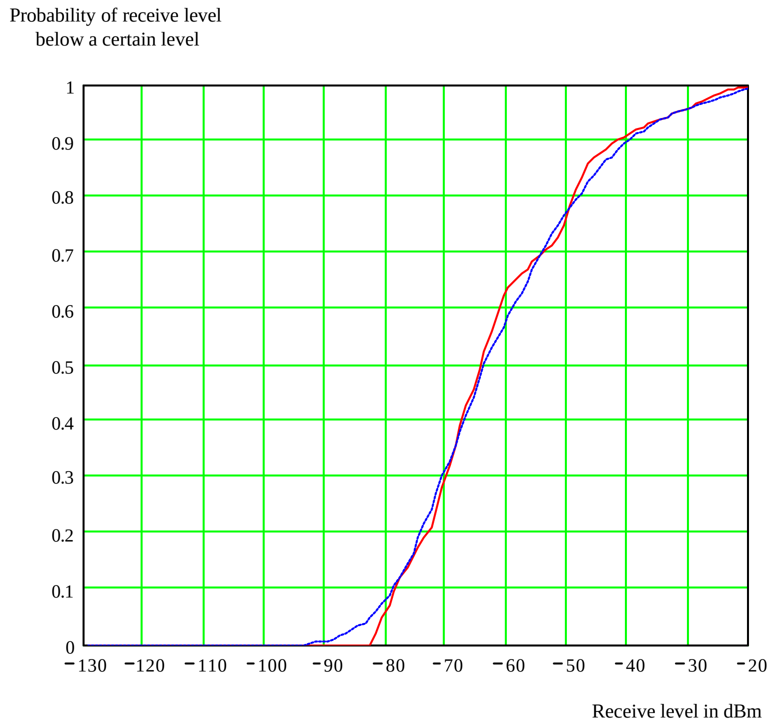


Figure 5-2a. Cumulative distribution of receive level for a large office building with the interfering system on all floors.

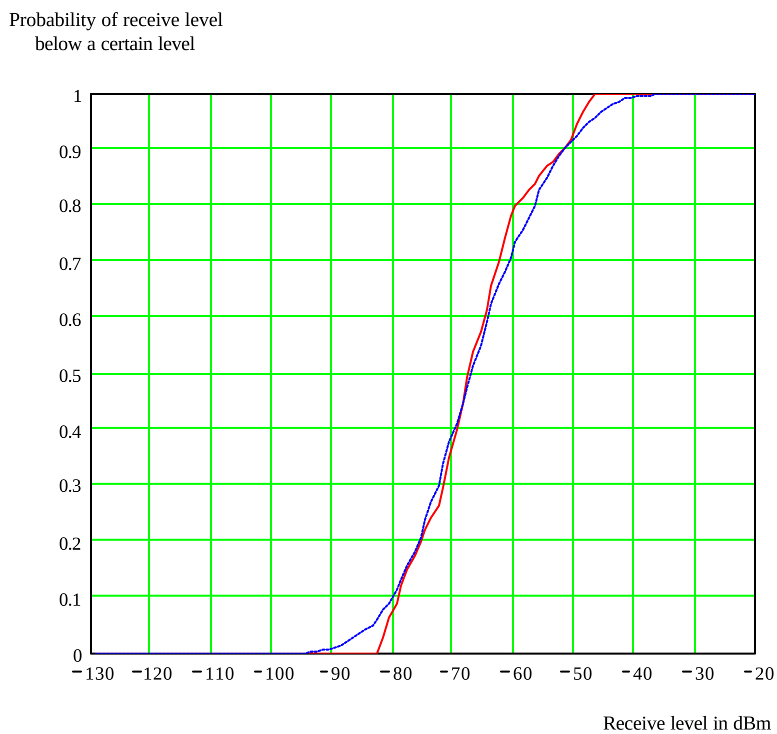


Figure 5-2b. Cumulative distribution of receive level for a large office building with no interference system on victim system floor.

The dotted line includes the effect of shadowing/fading. The shadowing/fading standard deviation is 5.7 dB.

The last column of each table gives the power level reduction of the 4 MHz bandwidth WBFH system necessary to produce the same interference as the 1 MHz bandwidth system. The bandwidth correction factor is 2.6 for the 1 MHz Bluetooth and 802.11 FH victim system and it is 1.19 for the IEEE 802.11b victim system. The power level correction for the victim filtering effect (β) is 4 dB for the 1 MHz Bluetooth and IEEE 802.11 FH victim systems and it is 0 dB for 802.11b victim system. The source for the table is figure 5b.

The typical IEEE 802.11 frequency hopping power level for WLAN applications is +20 dBm. At this power level, an IEEE 802.11 frequency hopping system would cover the complete floor at a minimum receiver level of –70 dBm. Thus, this configuration can be approximately compared to case where the interferer region and LAN cell covers the same area in the LMSC model (r_t =1 in table A4-2). Table 5-1a shows a necessary power reduction of 28 dB in the 4 MHz bandwidth system to equalize interference, while table A4-2 of the LMSC model extension indicates a necessary reduction of 31.5 dB. This comparison is only approximate because the LMSC table considers a distribution of receiver levels within the LAN cell and only the receiver level at the cell edge is considered here. Also, the effect of other floors and a different configuration shape apply here. Nevertheless, the comparison is very close and this actual physical example substantially verifies the LMSC model.

The Bluetooth power level is 0 dBm. This power level results in a mean receiver level at 10 meters of –60 dBm for Bluetooth with the model used. The –70 dBm value represents the minimum receiver level with a 10 dB fade/shadowing effect. Thus, -70 dBm represents a typical design value for achieving a 10 meter range in a Bluetooth picocell. This is approximately the conditions for an interferer radius to communication radius ratio of 4 (r_t =4 in table A4-2). Table A4-2 indicates that the power equalization reduction should be somewhat in excess of 29.5 dB at r_t =5 (the nearest ratio in the table) while table 5-1a shows 28 dB. This is also a close agreement.

Note in figure 5-2a, that when the tolerable interference level is very low (-80 to –90 dBm), virtually all of the interfering systems interfere and a large reduction in power level is necessary before any significant effect is realized. At the relatively higher tolerable levels of interference of (above about –80 dBm) the effect is less. At these higher levels, the effect on an IEEE 802.11b direct sequence system is 4 dB. This is consistent with the conclusion of the LMSC paper that bandwidth widening alone has only a small effect on direct sequence systems.

Office building floors up to about this size (80 meter linear dimension) can be covered by a single IEEE 802.11 LAN cell at the current power levels. Buildings slightly larger would require two cells. The necessary WBFH power reduction for equal interference with NBFH systems is less for the larger buildings that require more than one cell. The LMSC results of Table A4-2 indicate the necessary reduction for a floor with about two times this linear dimension would require a 24 dB reduction, compared to the 32 dB computed for the LMSC model for this building.

Table 5-1b shows that when the interfering system is excluded from the victim floor the relative interfering effect of the WBFH system is about 6 dB less than when interference exists on all floors.

In summary, the necessary power reduction for a WBFH system to neutralize the bandwidth increase is about 28 dB for this building when interfering transmitters are located on all floors and about 22 dB if the interferer system is excluded from the victim floor.

6.0 Large Apartment Building

This is a large multiple floor apartment building (80x12 meter, 5 floors). The floor attenuation is 20 dB for single floor separation and 30 dB for two floors. The attenuation of the walls separating the units is 10 dB per wall.

Table 6-1 was prepared from the probability distribution graphs of figures 6-2a and 6-2b. The building dimensions are illustrated in figure 6-1 along with an illustration of the constant average receive levels contours at 1 watt transmitter power. Figures 6-2a and 6-2b give the receiver level probability distributions.

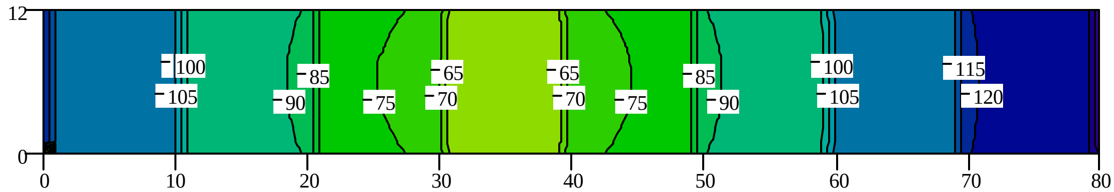
The last column of the table gives the power level reduction of the 4 MHz bandwidth WBFH system necessary to produce the same interference as the 1 MHz bandwidth system. The bandwidth correction factor is 2.6 for the 1 MHz Bluetooth and 802.11 FH victim system and it is 1.19 for the IEEE 802.11b victim system. The power level correction for the victim filtering effect (β) is 4 dB for the 1 MHz Bluetooth and IEEE 802.11 FH victim systems and it is 0 dB for 802.11b victim system.

Table 6-1. Necessary power reduction with 4 MHz bandwidth WBFH for large apartment building.

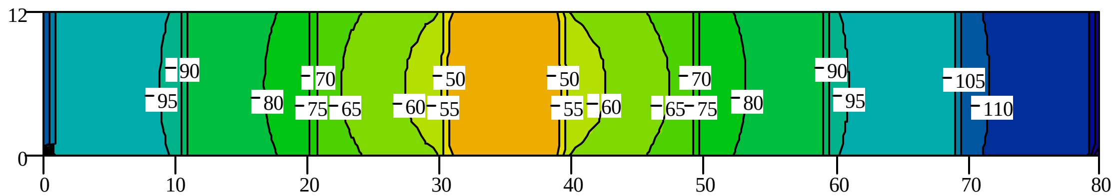
			Necessary WBFH power reduction	
Victim system	Target receive level of victim system	Tolerable interference level from 1 MHz FH	Interferers in all units	Interferers excluded from the victim unit
Bluetooth or 802.11 FH with a power increase	-40 dBm -50 dBm	-60 dBm -70 dBm	9 dB 13 dB	10 dB 12 dB
Bluetooth or 802.11 FH	-50 dBm -60 dBm -70 dBm	-70 dBm -80 dBm -90 dBm	13 dB 18 dB 22 dB	12 dB 16 dB 22 dB
802.11b DS at 11 Mb/s	-60 dBm -80 dBm	-70 dBm -90 dBm	5 dB 5 dB	4 dB 6 dB

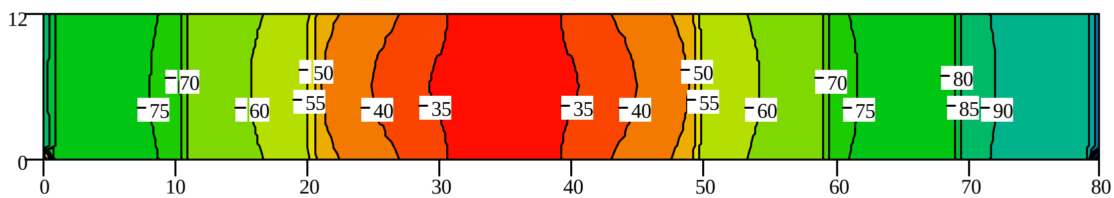
The typical IEEE 802.11 frequency hopping (FH) system power level is 20 dBm and the Bluetooth system power is 0 dBm. This leads to about –50 dBm mean receiver level for an IEEE 802.11 transmitter and –70 dBm for a Bluetooth transmitter at maximum range within an apartment. The optimum power level for a 1 MHz frequency hopping system with Bluetooth and IEEE 802.11 modulation for use in homes and apartments would be about 10 dBm (10 mW). This would allow about a 10 dB fade margin and provide reliable operation in the absence of other interference. The mean power level at maximum range for such a system would be about -60 dBm.

The relative level for equivalent interference of a 4 MHz bandwidth frequency hopping system with a 1 watt, 1 MHz bandwidth system for this hypothetical system with optimum transmitter power would be -16 dBW = 25 mW in this large apartment building.

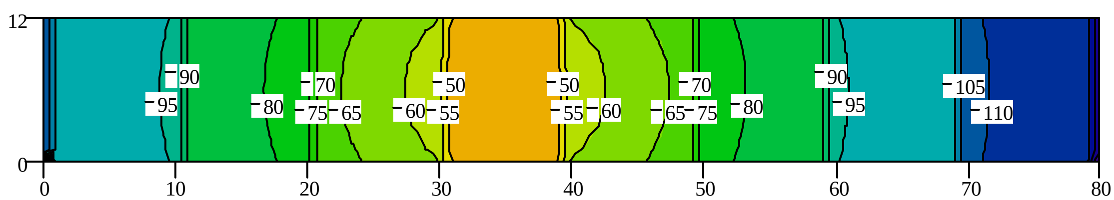


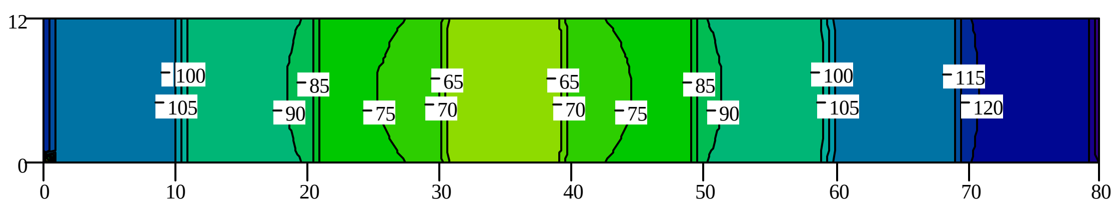
Upper floor





Middle most floor





Lower floor

Figure 6-1. Receiver levels in a large apartment building with a 10 dB wall every 10 meters. The levels are those that would be produced by a transmitter of 1 W power level in the middle most apartment. By reciprocity, the level produced at the middle point of the building would be the same if the transmitter was located on the corresponding equal level locus.

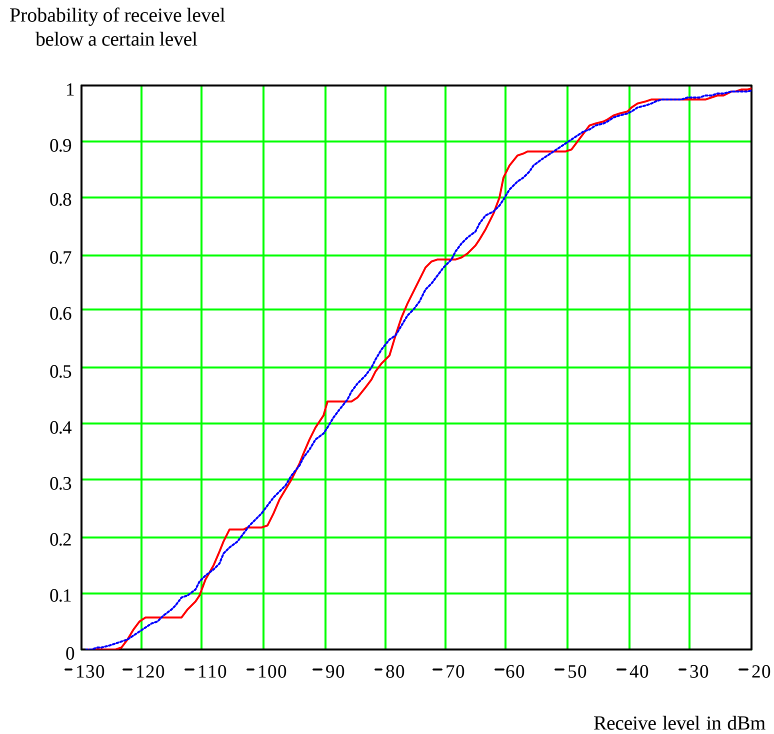


Figure 6-2a. Cumulative distribution of receiver level in a large apartment building with interferers in all apartments units.

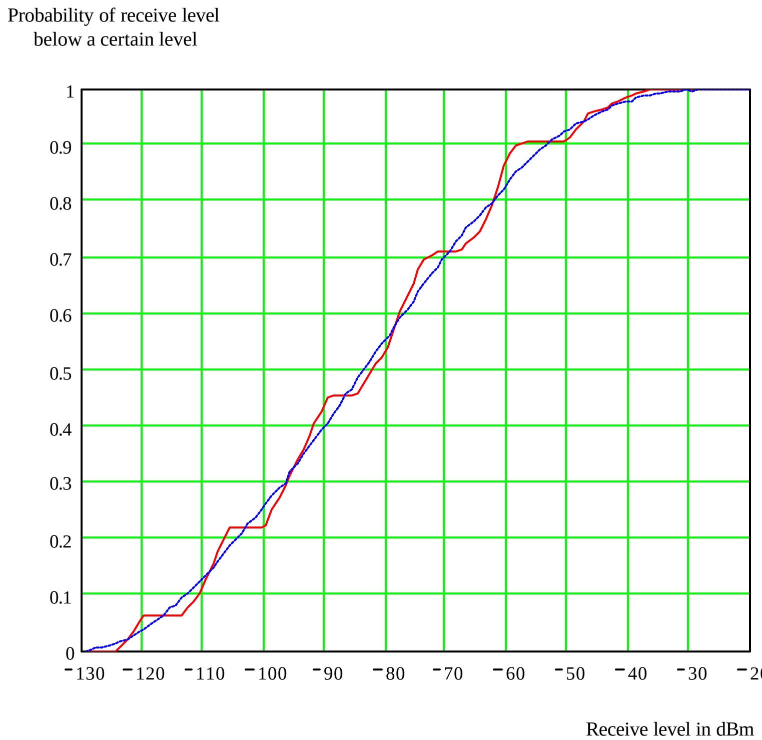


Figure 6-2b. Cumulative distribution of receiver level in a large apartment building with no interferers in the victim apartment units.

7.0 Smaller Multiple Floor Apartment Building

This is a multiple floor apartment building that is smaller than that of section 6 (50x12 meter, 5 floors). Floor and wall attenuation values are the same as in section 6. The floor attenuation is 20 dB for single floor separation and 30 dB for two floors. The attenuation of the walls separating the units is 10 dB per wall.

Table 7-1 was prepared from the probability distribution graphs of figures 7-2a and 7-2b. The building dimensions are illustrated in figure 7-1 along with an illustration of the constant average receive levels contours at 1 watt transmitter power. Figures 7-2a and 7-2b give the receiver level probability distributions.

The last columns of the table give the power level reduction of the 4 MHz bandwidth WBFH system necessary to produce the same interference as the 1 MHz bandwidth system.

Table 7-1. Power reduction with 4 MHz bandwidth WBFH for smaller multiple floor apartment building.

Victim system	Target receive level of victim system	Tolerable interference level from 1 MHz FH	Necessary WBFH power reduction: Interferers in all units	Necessary WBFH power reduction: Interferers excluded from the victim unit
Bluetooth or 802.11 FH with a power increase	-40 dBm -50 dBm	-60 dBm -70 dBm	10 dB 12 dB	7 dB 10 dB
Bluetooth or 802.11 FH	-50 dBm -60 dBm -70 dBm	-70 dBm -80 dBm -90 dBm	12 dB 18 dB 23 dB	10 dB 16 dB 22 dB
802.11b DS at 11 Mb/s	-60 dBm -80 dBm	-70 dBm -90 dBm	4 dB 7 dB	3 dB 7 dB

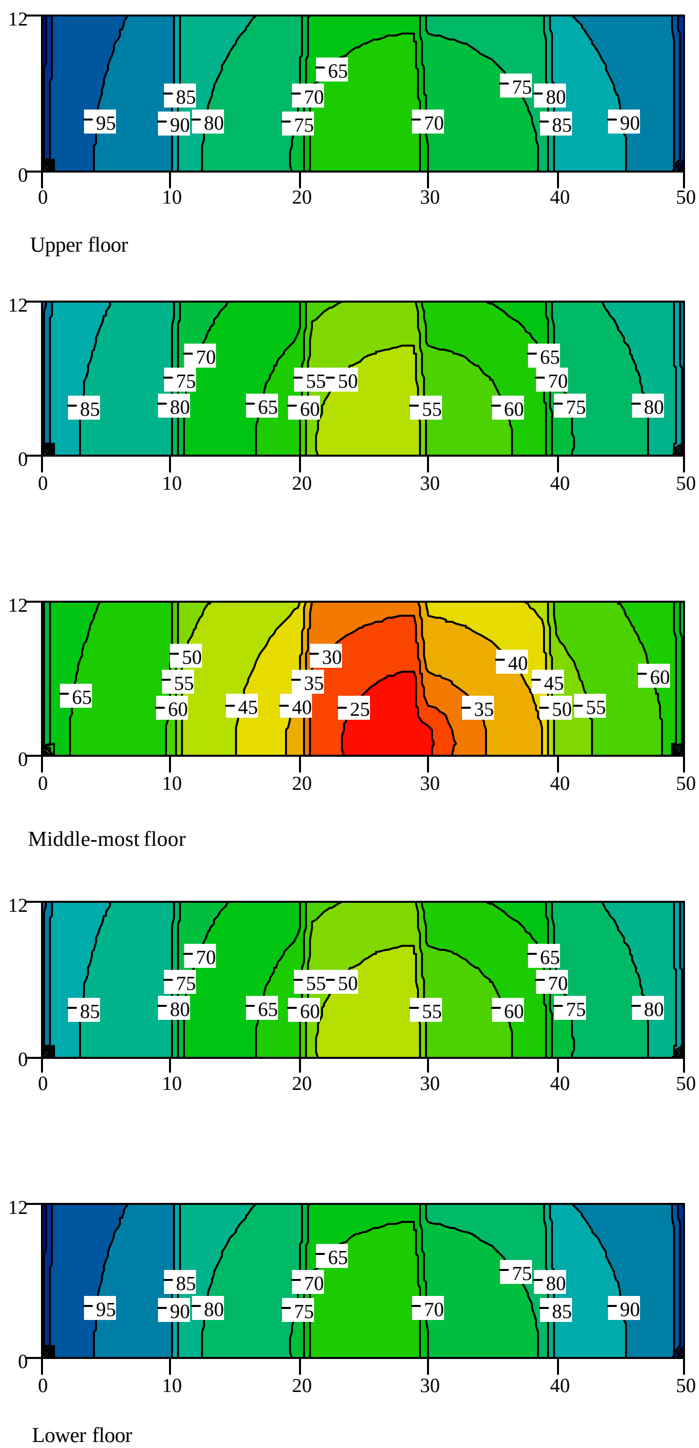


Figure 7-1. Receiver levels in a smaller multiple floor apartment building with a 10 dB wall every 10 meters.

The levels are those that would be produced by a transmitter of 1 W power level in the middle most apartment near a wall. By reciprocity, the level produced at the middle point of the building would be the same if the transmitter was located on the corresponding equal level locus.

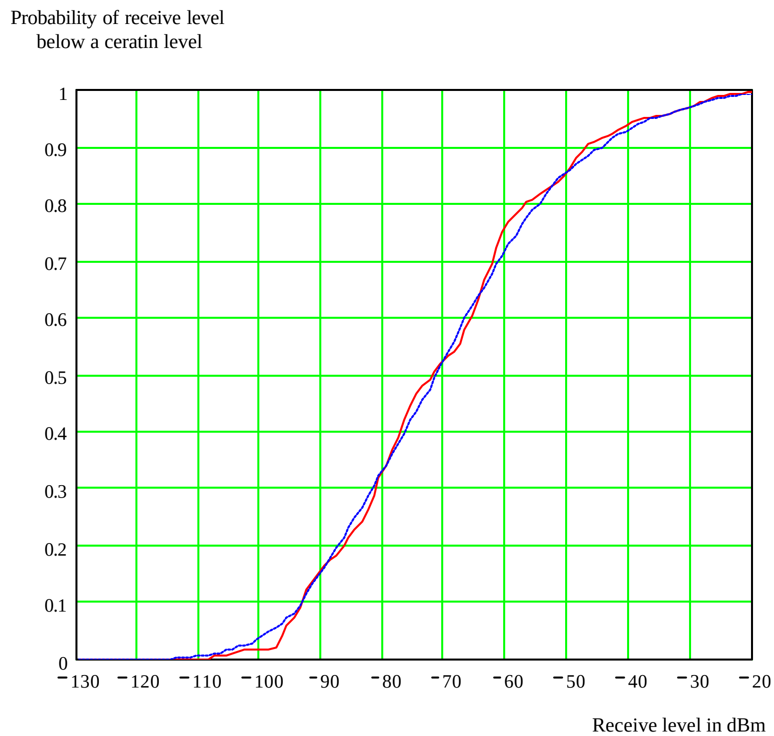


Figure 7-2a. Cumulative distribution of receiver levels in a smaller multiple floor apartment building with interferers in all apartments units.

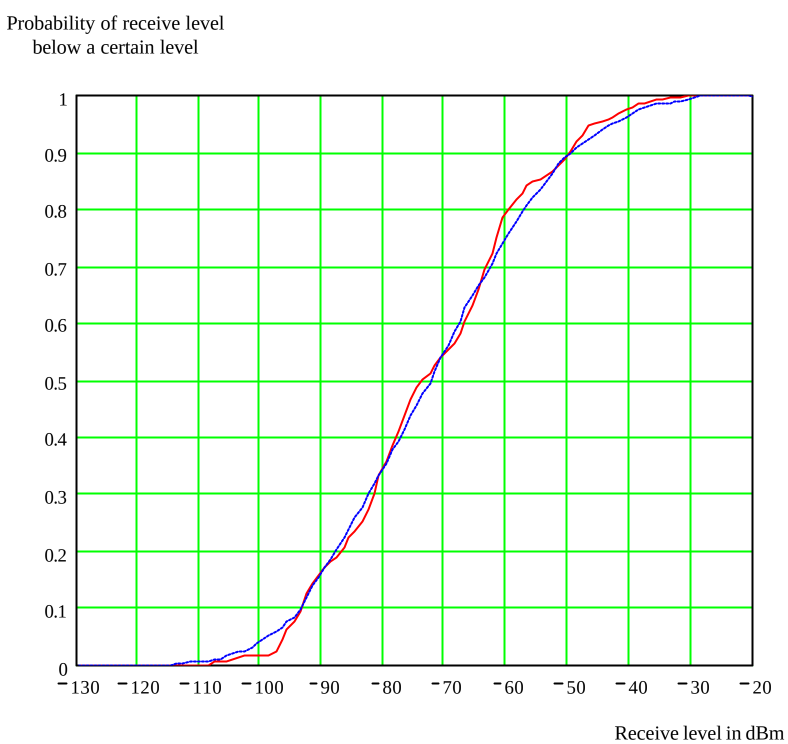


Figure 7-2b. Cumulative distribution of receiver level in a smaller multiple floor apartment building with no interferers in the victim apartment units.

8.0 Two Floor Apartment Complex

This is an apartment complex typical of many in the US. It consists of three buildings including 24 apartment units. The distance between adjacent building walls is 10 meters.

Internal floor and wall attenuation values are the same as in the previous examples. The floor attenuation is 20 dB for the single floor. The attenuation of the walls separating the internal units is 10 dB per wall. The external wall attenuation is somewhat different for each wall. The external wall attenuation between the first floors of the building on the left (nearest the victim receiver) and the victim apartment is 20 dB, while that on the right is 35 dB. This accounts for the possibility of windows between the nearer building. The external wall attenuation between the victim apartment unit on the lower floor and units on the upper floor is 10 dB greater than that between the same floors; that is, 30 dB to the nearest building (on the left) and 45 dB to the farther building (on the right).

Table 8-1 was prepared from the probability distribution graphs of figure 8-2a and 8-2b. The building dimensions are illustrated in figure 8-1 along with an illustration of the constant average receive levels contours at 1 watt transmitter power. Figures 8-2a and 8-2b give the receiver level probability distributions.

The last column of the table gives the power level reduction of the 4 MHz bandwidth WBFH system necessary to produce the same interference as the 1 MHz bandwidth system. Note that an interference level below -90 dBm (-70 dBm -20 dB C/I) has no effect on the table 8-1 results. Thus, the building on the right contributes little to the interference.

Table 8-1. Necessary power reduction with 4 MHz bandwidth WBFH for a two floor apartment building complex.

			Necessary WBFH power reduction	
Victim system	Target receive level of victim system	Tolerable interference level from 1 MHz FH	Interferers in all units	Interferers excluded from the victim unit
Bluetooth or 802.11 FH with a power increase	-40 dBm -50 dBm	-60 dBm -70 dBm	10 dB 14 dB	8 dB 12 dB
Bluetooth or 802.11 FH	-50 dBm -60 dBm -70 dBm	-70 dBm -80 dBm -90 dBm	14 dB 20 dB 24 dB	12 dB 17 dB 22 dB
802.11b DS at 11 Mb/s	-60 dBm -80 dBm	-70 dBm -90 dBm	4 dB 7 dB	4 dB 6 dB

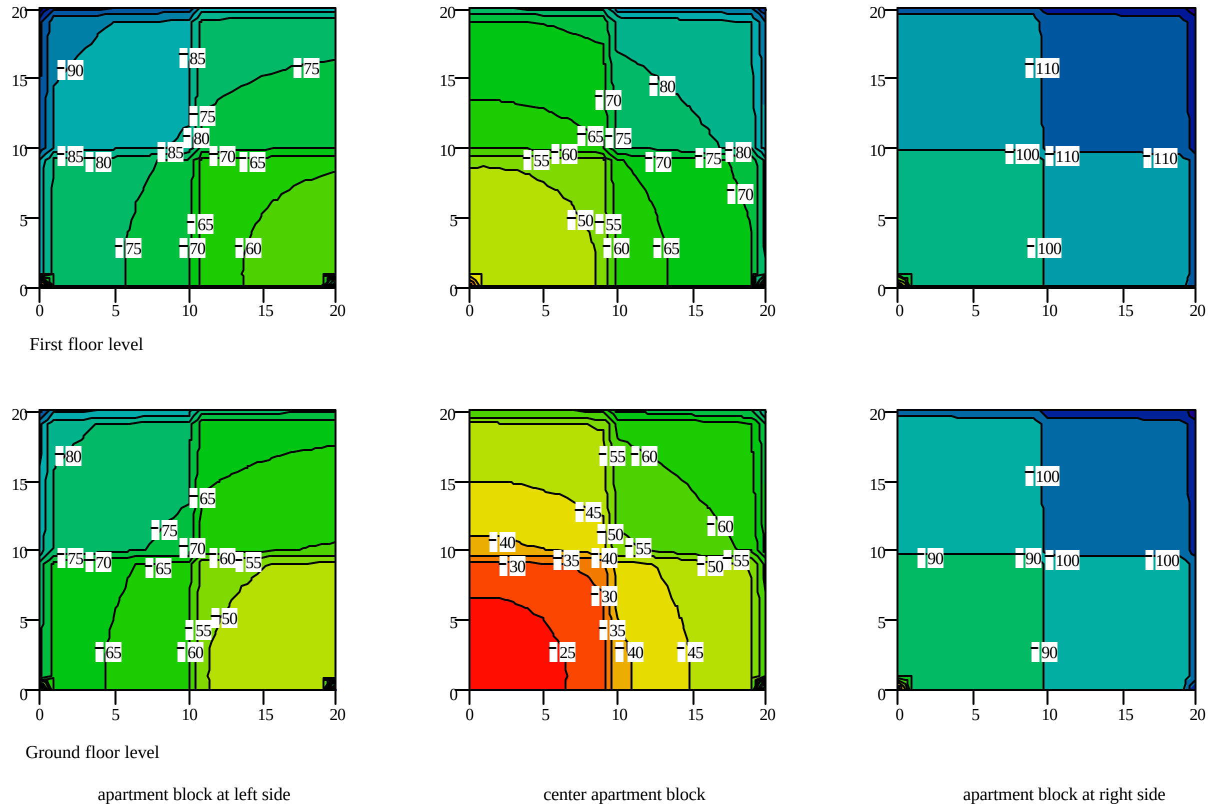


Figure 8-1. Receiver levels in a two-floor apartment building complex.
The levels are those that would be produced by a transmitter of 1 W power level in the middle most apartment near a wall. By reciprocity, the level produced at the middle point of the building would be the same if the transmitter was located on the corresponding equal level locus. The width of the space between buildings is 10 meters. See the text for the wall and floor attenuation.

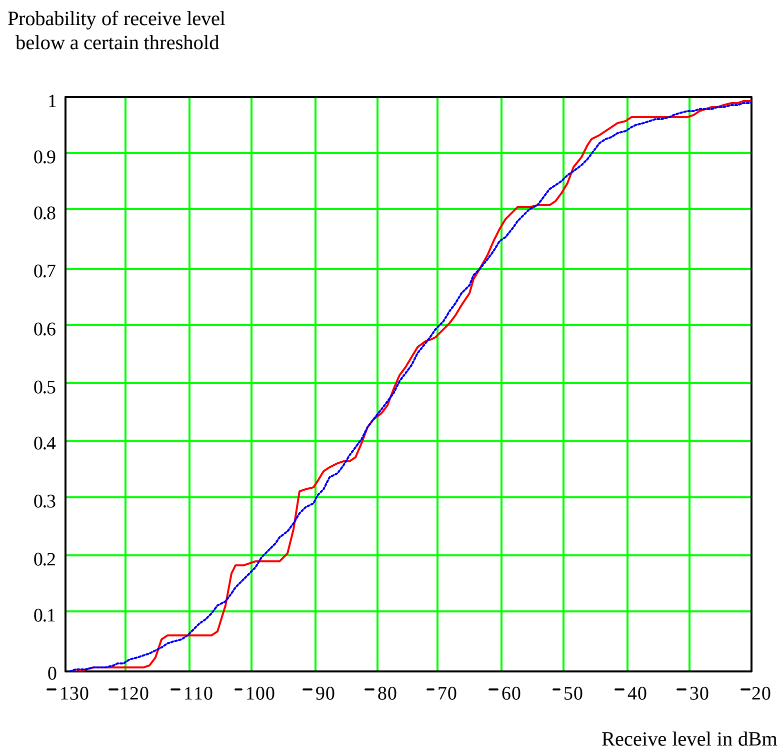


Figure 8-2a: Cumulative distribution of receiver levels in two-floor apartment building complex with interferers in all apartments units.

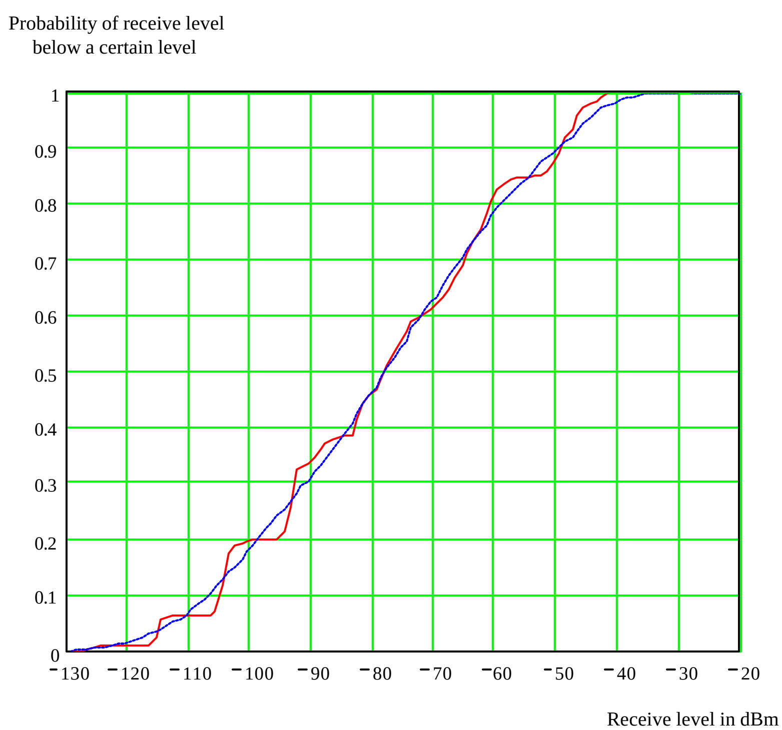


Figure 8-2b. Cumulative distribution of receiver level in a two-floor apartment building complex with no interferers in the victim apartment unit.

9.0 Summary of Apartment Interference and Comparison to the TIA model

Table 9 gives a summary of the results of the apartment building comparisons.

The highest (–60 dBm) receiver level is appropriate for comparing the effect of a WBFH system on an IEEE 802.11 frequency hopping system with a power level of 100 mW. The lowest (-70 dBm) is appropriate for a comparison of the effect on a Bluetooth system at a 1 mW power level. A 1 MHz bandwidth system using the IEEE 802.11 and Bluetooth modulation designed with an appropriate power level for this application would operate at about 10 mW. In this case, the appropriate receiver level for comparison is the –60 dBm middle level.

Table 9: Summary comparison of necessary WBFH power reduction necessary to equalize interference in the apartment buildings analyzed.

Apartment Building	Receiver level = -50 dBm	Receiver level = -60 dBm	Receiver level = -70 dBm
Large multiple floor (section 6)	13 dB	18 dB	22 dB
Smaller multiple floor (section 7)	12 dB	18 dB	23 dB
Two floor building complex (section 8)	14 dB	20 dB	24 dB

There are interferers in all units including the victim unit. The relative power levels are about 2 dB less when the victim unit is excluded.

The apartment buildings are relatively large compared to the interference range of the receiver. In other words, the interferer system deployment area is larger than the area covered by the victim receiver interference range. The interference would not be very higher in larger buildings. This is the reason that all buildings show about the same effect. For this same reason, the relative interference effect would not likely be greater in larger buildings, since the added interference volume would be out of range of the victim receiver. On the other hand, the interference effect would be expected to be worse (require a higher power reduction) for smaller buildings.

The IEEE LMSC model is not appropriate here because of the relatively large area of interferer deployment. The TIA model would be more appropriate if the wall attenuation could be considered to increase the value of the attenuation exponent α. Equation A3-5a2 from the appendix is derived from equation 5a of the TIA paper. It applies when the full ISM spectrum is used and the victim bandwidth is less than the frequency hopping bandwidth. The equation is

$$P = k_1 B_t^{a/2} W_{FH}^{(2-a)/2} \quad \textbf{\textit{for}} W_V \leq W_{FH} \qquad \text{(A3-5a2)}$$

Thus, the necessary power level reduction is proportional to the reciprocal of the frequency hopping bandwidth ($1/W_{FH}$) raised to the power (α-2)/2. A value of α of about 8 would give approximately the observed 18 dB value for the –60 dBm victim receiver level.

The TIA model is not fully appropriate because the effect of the wall attenuation cannot be approximated very closely by the linear attenuation versus log distance equation assumed. The slope of the attenuation versus log distance curve actually increases with distance due to the walls. However, the same phenomenon occurs; the presence of the walls causes the relative interference effect to be higher than predicted by the non-obstructed TIA model.

10. Conclusion

The relative interference effect of a 4 MHz bandwidth WBFH system is about 28 dB in a typical large office building with a long rectangular shape and multiple floors. This agrees well with the IEEE LMSC model that predicts a 31.5 dB interference effect in a two-dimensional circular configuration. The effects of the multiple floors and the rectangular geometry are relatively insignificant.

The effect is about 22 dB if interfering transmitters are excluded from the victim system floor.

The effect can be expected to be greater in smaller buildings and less in larger buildings. For this reason, a very large building was selected for analysis. The LMSC model predicts the equalizing power difference to be 7 dB less in a building of 4 times the area per floor.

Three typical relatively large apartment buildings were also analyzed. The relative interference effect was very consistent across these buildings and ranged form 18 to 20 dB with interferers distributed evenly throughout the building when the a victim system power level is optimized for the application. The effect is less with higher power level victim systems and higher for lower power level systems. It is 13 to 14 dB with a power level approximately that of the current IEEE 802.11 standard systems and about 22 to 24 dB with current Bluetooth power levels.

The interference effect is about 2 dB less if the interfering system is excluded from the victim apartments.

Apartment buildings with walls between units tend to behave in accordance with the model of the referenced TIA paper. The wall attenuation tends to increase the path attenuation. An attenuation exponent characterizes path attenuation with distance in this model. The TIA paper projects a high relative interference effect with a high value of the attenuation exponent. The effective attenuation exponent for the 18 dB equalizing power difference was shown to be about 8.

APPENDIX A: SUMMARY AND EXTENSION OF THE TIA WIRELESS AND LMSC INTERFERENCE MODELS

The TIA and LMSC papers previously filed analyze the effect of wide bandwidth frequency hopping in generalized configurations and with parameters previously considered in the WBFH Docket and a previous OET docket. This previous work is used as a guide for the further study. These previous papers are summarized in this appendix and extended to better cover the parameters now under consideration in the WBFH Docket.

A1. Model Comparison and Applicability

The interference model used in TIA Wireless (TIA henceforth) paper is summarized and extended for the WBFH case and the LMSC/Lucent (LMSC henceforth) paper is extended to the 4 MHz bandwidth case in this section.

Figure A1 illustrates the configurations appropriate for each model. Figure A1-1 illustrates the TIA model and Figure A1-2 illustrates the LMSC model.

The TIA model considers the interfering transmitters to be evenly distributed over an area large enough to cover the complete interference radius of a single receiver. The propagation exponent is assumed to equal 4. The propagation exponent and the wide area of interference deployment makes this an appropriate configuration model for examining the effect of frequency hopping systems on receivers located in positions in which they are susceptible to interference over a large region. Thus, the model is appropriate to analyze the effect of frequency hopping systems on non-Part 15 systems such as, for example, amateur repeaters.

The LMSC model considers the interfering transmitters to be evenly distributed over a smaller region. Instead of a single receiver, this model considers the victim transmission distances to be distributed over a circular cell with a Wireless Local Area Network (WLAN) access point centrally located. The interfering transmitters are deployed over a circular area with radius greater than of equal to that of the victim cell. This configuration is appropriate for WLANs in which distance or obstructions such as walls isolate the locations.

Interference is considered to be equal in the TIA model if the interference from two compared systems is present the same proportion of time for each system. Interference is considered to be equal in the LMSC model if the interference from two compared systems creates the same probability of data packet error for each system.

The TIA model yields a simple closed form solution dependent on the propagation exponent and relative bandwidths. On the other hand, the LMSC model results depend upon additional variables. These include victim Carrier to Interference (C/I) requirement, the interfere deployment radius to the WLAN cell radius ratio and the WLAN packet length to frequency hopper dwell time ratio. Both papers present the result as the necessary power level to maintain equal interference probability.

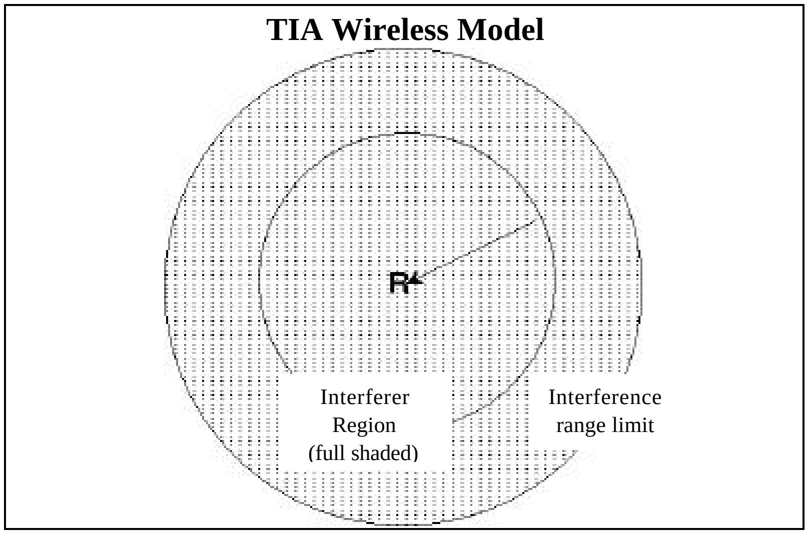
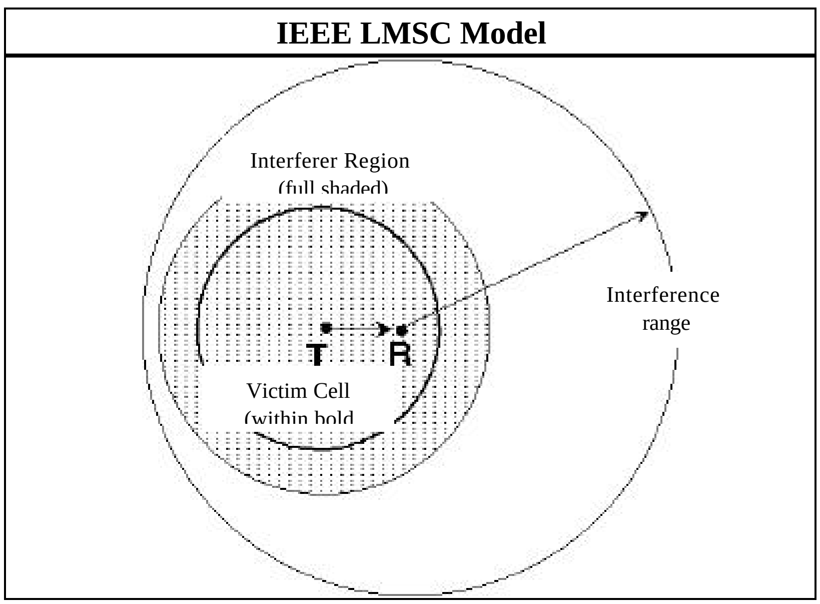


Figure A1-1



Figures A1-2

Figure A1: TIA and LMSC Frequency Hopping Interference Model Illustrations

The TIA Wireless model considers a single receiver surrounded by large region of frequency hopping interferers as in figure A1-1. The interference sources exist over the full interference range of the receiver. The LMSC/Lucent model considers a centralized local area network cell surrounded by a finite sized region of interfering devices as in figure A1-2. The TIA model is appropriate for victim receivers located outdoors in an urban or suburban region in which Part 15 interfering frequency hopping systems exist. The LMSC model considers a confined region in which two Part 15 systems exist, one of them is an interfering frequency hopping system.

A2. Parameters

The two compared models used different designations for the system parameters. These parameters and their definitions are given in table A1. In this paper, the number of channels will be designated by n. In other cases the TIA parameter designation is used if it is defined. The LMSC parameter designation is used when the TIA parameter is not defined.

Table A1. Cross Reference between the Parameters of the TIA and LMSC Documents.

TIA Wireless parameter	LMSC/Lucent parameter	Definition
W_{FH}	B_h	Frequency hopping bandwidth
W_v	$k_r B_v$	Victim system receiver bandwidth
Not needed	B_v	Victim emission bandwidth
B_{ss}	nB_h	Total spectrum used by the interfering frequency hopping system
B_{ISM}	83.5 MHz	Full ISM bandwidth
Not needed	B_t	Product of the minimum number of hopping channels and the maximum permitted bandwidth (75 MHz per 15.247)
Not needed	B_{ih}	Interference bandwidth
α	α	Propagation exponent
m	n	Number of frequency channels used by the frequency hopping system

A3. The TIA Paper applied to the Current Case

The TIA paper was written for OET docket 96-8. The principal subject evaluated by the paper related to this docket and was concerned with the effect of lowering the number of hopping channels while maintaining an unchanged frequency hopping channel bandwidth limit. The conclusion of the document is that to maintain equal interference when the required number of channels is reduced, while maintaining the same bandwidth, the power level should be proportional to the minimum spectrum usable by the frequency hopping system. Equation 10 from that paper is repeated below.

$$P_1 = \left(\frac{B_{SS}}{B_{ISM}} \right)^2 . \qquad (10)$$

Since the minimum value of B_{ss} is proportional to n ($B_{ss} = nW_{FH}$ if contiguous channels are used), the power should be proportional to n^2 to maintain equal interference by the interference level definition of the TIA paper.

However, when the model used in the TIA paper is used and the overlapping channels condition of the Notice are imposed, the linear power reduction of the Notice can be shown to be appropriate. Thus, the proposed linear power reduction for wide bandwidth is appropriate for showing the effect on non-Part 15 services and Part 15 services located outdoors and subject to interference from a large geographical region. The LMSC paper, on the other hand, shows that the inverse linear relationship is not sufficient for isolated systems.

The parameters of the TIA paper will be used to show the inverse linear relationship for the infinite interferer region case. Refer to the TIA paper for the following development.

The area of the interference zone is given in equation 1 of the TIA paper. C_v is an arbitrary constant, W_V is the victim bandwidth, W_{FH} is the frequency hopper bandwidth, P is the power level and α is the propagation exponent. Equation 1 of the TIA paper is repeated here as equation A3-1.

$$A = pr^2 = \begin{cases} C_V \left(\frac{W_V}{W_{FH}} P \right)^{2/a} & \text{for } W_V \le W_{FH} \\ C_V P^{2/a} & \text{for } W_V \ge W_{FH} \end{cases} \qquad \text{(A3-1)}$$

Consider wide bandwidth overlapping channels occupying B_t of the available ISM bandwidth. The docket 99-231 proposal is for B_t = 75 MHz. The TIA paper referred to the full 82.5 MHz of the 2.4 GHz band as B_{ISM}, thus B_t is slightly less than B_{ISM}. Let B_{ih} be the frequency range over which the frequency hoppers interfere with the victims. B_{ih} is always greater than the larger of W_V and W_{FH} and is approximately equal to $W_V + W_{FH}$ when the values are nearly equal and when the modulation technique that is proposed for the WBFH system is used. Frequency hopping systems complying with IEEE 802.11 and Bluetooth also use this modulation technique.

Equation 2 of the TIA paper gives the mean number of interferers K. This parameter becomes, for the current case,

$$K = rA\left(\frac{B_{ih}}{B_t} \right) \qquad \text{(A3-2)}$$

in which ρ is the density of transmitters.

Then, in the same manner as equations 4a and 4b of the TIA paper, but with the full band overlapping case

$$K = \left(\frac{W_V}{W_{FH}} P \right)^{2/a} \frac{r C_V B_{ih}}{B_t} \quad \textbf{\textit{for}} W_V \le W_{FH} \qquad \text{(A3-4a)}$$

$$K = P^{2/a} \frac{r C_V B_{ih}}{B_t} \quad \textbf{\textit{for}} W_V \ge W_{FH} \qquad \text{(A3-4b)}$$

These leads to the parallels of equations 5a and 5b of the TIA paper

$$P = k_1 \frac{W_{FH}}{W_V} (B_{ih})^{-a/2} \quad \textbf{\textit{for}} W_V \le W_{FH} \qquad \text{(A3-5a1)}$$

$$P = k_2 \left(\frac{B_t}{B_{ih}} \right)^{a/2} \quad \textbf{\textit{for}} W_V \ge W_{FH} \qquad \text{(A3-5b1)}$$

In the general case B_{ih} is slightly larger than the larger of W_V and W_{FH}. It approaches the larger of the two values if the ratio of bandwidths is high. Thus, for large bandwidth differences, equation 3-5a1 shows P to be approximately proportional to W_{FH} raised to the exponent (2-α)/2. The value of the propagation exponent α is assumed to be 4 in the TIA paper. With this value, Equation 3-5a1 for the low victim bandwidth gives a power level that is approximately inversely proportional to W_{FH}. This leads to the inverse bandwidth-power concept.

The effective value of the propagation exponent is higher dwelling units such as apartment buildings with absorbing and blocking walls. Thus, in home applications, equation A3-5a1 indicates that a power reduction in excess of a linear bandwidth relationship is necessary for wide bandwidth frequency hopping systems.

Equation 3-5b1 for the wide victim bandwidth gives a smaller variation of the necessary power with bandwidth than does equation 3-5a1. Thus, the full band non-overlapping channel case is relatively benign to victim systems with wide bandwidths.

<u>The TIA model with a constraint</u>.

The TIA paper assumes, and European Telecommunication Standards Institute (ETSI) rules permit, systems with narrow bandwidth frequency hopping channels to use a reduced set of frequencies. This leads to the inverse squared bandwidth frequency relationship cited above. If a constraint is added that the system must use the complete, or nearly complete, ISM band then this relationship can be relaxed.

If it is required that n = B_t/W_{FH} then a wide bandwidth frequency hopper is constrained to use at least B_t of hopping bandwidth. In this case equations 5a and 5b of the TIA paper become

$$P = k_1 B_t^{a/2} W_{FH}^{(2-a)/2} \quad \textit{\textbf{for}} W_V \le W_{FH} \qquad \text{(A3-5a2)}$$

$$P = k_2 B_t^{a/2} \quad \textit{\textbf{for}} W_V \ge W_{FH} \qquad \text{(A3-5b2)}$$

These equations are nearly the same as A3-5a1 and A3-5a2. They result from the former equations if B_{ih} is set equal to the larger of W_V and W_{FH}. Thus, the same conclusions hold.

If the constraint is imposed, then the linear power reduction is sufficient.

It can thus be concluded that if the full spectrum is used for either overlapping channels or for non-overlapping channels, equal interference (as defined in the TIA model) requires an inverse linear power-bandwidth relationship. Thus, the inverse linear power-bandwidth is appropriate for the case where the interferers are distributed over a wide area with homogenous propagation. However, the IEEE LMSC paper shows that this is not sufficient if the interferer system is limited in deployment area.

A4: The LMSC/Lucent Papers for a 4 MHz WBFH Bandwidth with Extensions to the Bluetooth Case

The LMSC and Lucent papers compared the interference conditions for 3 and 5 MHz WBFH systems with that from a 1 MHz bandwidth system. The interfering power of the 1 MHz system used for comparison was 1 W and the victim power level was also 1 W. The analysis concentrated on the victim systems complying with IEEE 802.11. In addition, there was an error in figure 3-3 that led to about a 1/2 to 1 dB error in the results.

This appendix presents the corrected figure 3-3, extends the analysis to cover a 4 MHz WBFH bandwidth case and presents some results for lower victim power levels. The lower victim power levels correspond to those presently used in the 802.11 systems and in the Bluetooth standard. The development in the LMSC paper is used.

The bandwidth factor and the parameter β were analyzed more accurately in section **3.0** of this paper than in the LMSC paper. The more accurately determined values are used here. The values are:

Bandwidth factor = 2.6
β = 4 dB.

Figure A4-1 shows a corrected figure 3-3 of the LMSC paper. The curves in the original graph approached a lower asymptote for high power differences. The error in the LMSC results is in the order of 1 dB and is thus not significant in the conclusions of that paper.

Table A4-1 below illustrates how the graph is used to determine the necessary 4 MHz bandwidth WBFH system power reduction to equalize the interference probability with that produced by a 1 MHz bandwidth Narrow Band Frequency Hopping (NBFH) system. Both compared frequency hopping systems use slow frequency hoping. The C/I ratio of the table is 23 dB, which corresponds to a typical C/I requirement for a frequency hopping system complying with the IEEE 802.11 standard. The parameter r_t is the ratio of the interferer deployment region radius to the communication cell radius.

Table A4-1. Necessary Power Level Difference to Equalize WBFH Interference with 1 Watt Victim Power and Slow Frequency Hopping.

Interference region radius to cell radius ratio (r_t)	Percent Interfering at 1 MHz Interferer Bandwidth	Percent Required at 4 MHz Bandwidth = Previous Column/2.6	Power Difference Plus C/I - β (19 dB) for 4 MHz System. Reference figure A4-1	Power Difference to Equalize Interference. Equals 19 dB -Previous Column
1	98.9	38.0	-3	22 dB (6 mW)
2	94.1	36.2	4.2	14.8 dB (33 mW)
3	85.6	32.9	8.2	10.8 dB (83 mW)

This shows the necessary power reduction for an interfering 4 MHz bandwidth frequency hopping system that uses 75 MHz of spectrum (B_{ss} = 75 MHz) compared to the 1 W power level of an interfering 1 MHz bandwidth frequency hopping system using the same amount of spectrum. The C/I requirement of the victim system is 23 dB, which corresponds to a system complying with the IEEE 802.11 frequency hopping standard. The middle columns illustrate how figure A4-1 is used in the computation. The frequency hopping rate is assumed low enough that the fast hopping effect of the LMSC paper is neutralized.

When the victim power level is lower the necessary power level reduction in a WBFH system to compensate for the increased bandwidth is higher. Inspecting figure A4-1 shows this. A higher power difference (high ΔP) means the operating point of the graph is in the upper right region. The curves are nearly flat and near the 100 percent asymptote for normal size deployment region ratios (r_t). This means that nearly all of the devices transmitting on frequency will interfere. The power level must be decreased to a level below the break point of the curves before any reduction in the proportion interfering will be realized.

Table A4-2 shows the comparative power level when the NBFH interfering power level is 1 W and the victim power level is lower than 1 W. Most WLAN systems complying with the IEEE 802.11 standard now operate at a 100 mW level or less. The Bluetooth standard now specifies a 1 mW power level.

Note: Equation A3-5a1 shows the necessary power reduction for a single receiver centered in an infinite region of interferers. This predicts a value of $2.6^{-0.75}$ = 0.49 or 3.1 dB for r_t very large. Table A4-2 gives 2.5 dB for r_t = 20 and 1 W power level. Thus, there is close agreement between the two models as the LMSC model is made to approach the conditions of the TIA model.

Table A4-2. Necessary Power Level Difference to Equalize WBFH Interference with Various Levels of Victim Power and Slow Frequency Hopping.

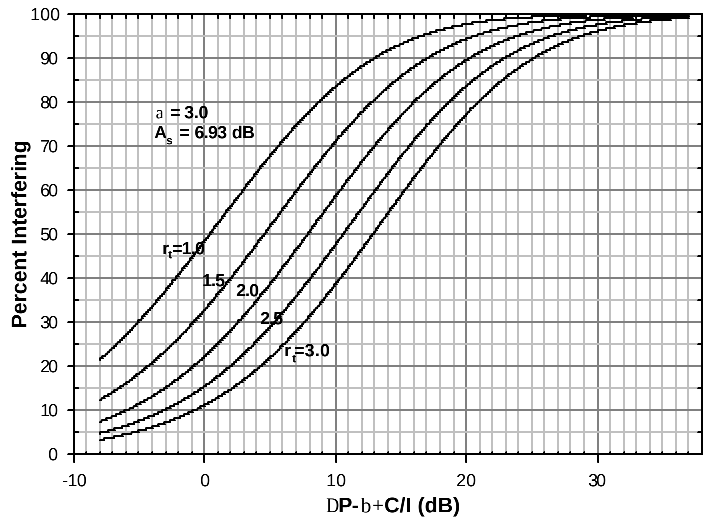
Interference region radius to cell radius ratio (r_t)	Power Difference to Equalize Interference at 1 W victim power level (dB) C/I = 23 dB	Power Difference to Equalize Interference at 100 mW victim power level (dB) C/I = 23 dB	Power Difference to Equalize Interference at 1 mW victim power level (dB) C/I = 20 dB
1	22 dB	**31.5**	48.5
2	14.8 dB	24.3	41.0
3	10.8 dB	19.5	36.0
5	6.5	13.5	**29.5**
10	3.2	7	20.5
20	2.5	3.5	12.5

This shows the necessary power reduction for an interfering 4 MHz bandwidth frequency hopping system that uses 75 MHz of spectrum (B_{ss} = 75 MHz) compared to the 1 W power level of an interfering 1 MHz bandwidth frequency hopping system. Each compared interfering system uses the same amount of spectrum. The 1 W and 100 mW columns apply to systems complying with the IEEE 802.11 standard with C/I = 23 dB. The 1mW corresponds to a system complying with the Bluetooth standard with a C/I ratio of 20 dB. The frequency hopping rate is assumed low enough that the fast hopping effect of the LMSC paper is neutralized.

The most prevalent interference region radius to cell radius ratio (r_t) for systems complying with the IEEE 802.11 standard is 1. However, Bluetooth is intended for operation at smaller cell sizes and the most prevalent ratio for Bluetooth is likely to be about 5 (range of about 1/5 that of IEEE 802.11). The bolded number in the last column is most appropriate for systems complying with the Bluetooth standard. Most systems complying with the IEEE 802.11 frequency hopping standard use power levels of 100 mW or lower, thus the bolded number in the 100 mW column is most appropriate for systems complying with the IEEE 802.11 standard.

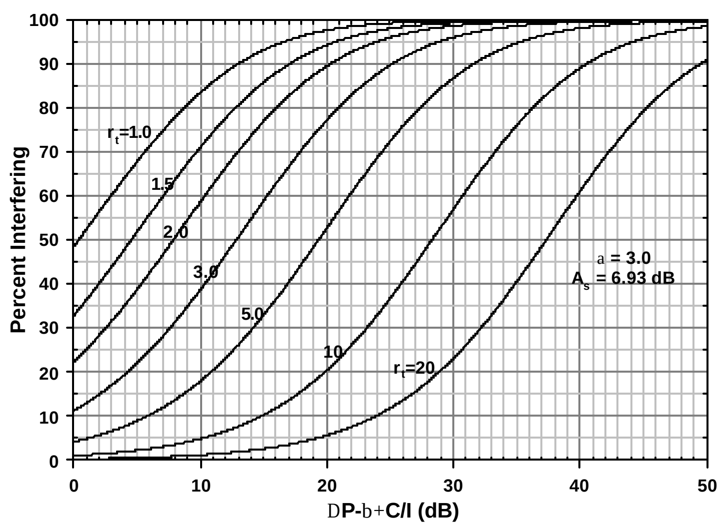
Thus, the necessary WBFH power levels to equalize interference with current systems is on the order of 30 dB even if the WBFH system uses only slow frequency hopping. This could be reduced to 20 dB if the current systems increase their power level by 10 dB.

Equation A5-5a2 from the TIA model is appropriate for the large interferer deployment area situation. This shows the necessary power level reduction to be proportional to the reciprocal of the frequency hopping bandwidth ($1/W_{FH}$) raised to the power $(\alpha-2)/2$. With $\alpha = 3.5$ and $W_{FH} = 1/W_{FH} = 0.25$, this yields about -4.5 dB. The table above gives -2.5 dB. The difference is within the computational accuracy of the table.



Proportion Interfering Vs. Differential Power Level

Figure A4-1a



Proportion Interfering Vs. Differential Power Level

Figure A4-1b

Figure A4-1. Proportion of devices interfering versus interferer to victim power level difference. Figure A4-1a is a corrected version of figure 3-3 of the LMSC paper and figure A4-1b is an extension of the figure appropriate for analyzing high interfering/victim power ratios such as can be expected for systems following the Bluetooth standard. The figure shows how the number of interfering transmitters change with the relative interferer to victim power dB differences. ΔP is the dB power difference, β represents the portion of the interfering power captured by the victim filter and C/I is the required carrier to interference ratio of the victim. The parameters are fully described in the LMSC paper